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HIGH CAPACITY OPTICAL JUKEBOX

Eastman Kodak Company

Dan Matukewicz, and Chris Williams

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13. ABSTRACT *(Maximum 200 words)*

Air Force Research Laboratory, Information Directorate has been performing research and development in the area of large capacity optical disk storage technology for several years. One area of particular interest is the development of an erasable, large-format (14-inch diameter) optical disk media and a suitable, high-performance optical recording head. A large-format disk provides for extremely large storage capacity in excess of 10 gigabytes with future expansion to 25 gigabytes. The ability to quickly and randomly access large data files is critical as the Air Force increasingly relies on digital imagery, maps, charts and video for multi-sensor exploitation, aircraft mission planning and other time-sensitive military applications. The origianl objective of this effort was to develop and deliver an automated optical disk jukebox which held 50 erasable optical disks. However, due to changing business conditions, the effort was redirected toward an investigation of those high-risk technologies which may limit future product commercialization. An important element of this effort was to leverage the contractor's current Write-Once, Read Many (WORM) optical jukebox product which promised to reduce the overall technical risk and shorten the development schedule. With today's emphasis on commercial off-the-shelf (COTS) solutions, this approach developed optical media and a disk drive architecture that maps well into future commercialization activities to the benefit of both parties.

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Table of Acronyms

ADM	Advanced Development Model
AlN	Aluminum Nitride
EKA	Eastman Kodak Actuator (in place of the Olympus/TAOHS actuator)
FWHM	Full Width Half Max
HEB	Head Electronics Board
HCOJ	High Capacity Optical Jukebox
HIEB	Head Interface Electronics Board
HMI	Head Media Interface
HSM	Hierarchical Storage Management
MO	Magneto-Optic
MODS	Magneto-Optic Development Spin-Stand
ORP	Optimum Recording Power
PLD	Programmable Logic Device
RedKOH	Red (680 nm wavelength) Kodak Optical Head
SDL	Spectra Diodes Laboratory
TES	Tracking Error Signal
WORM	Write Once Read Many
2000E	System 2000 Enhanced (25 GB drive / media)

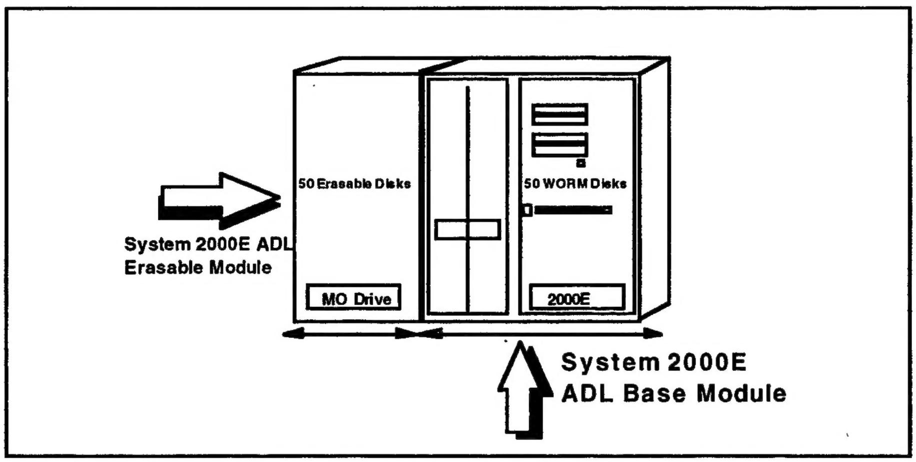
1. 0 INTRODUCTION

1.1 Program Overview

The objective of the Rome Laboratory Contract (# F30602-94-C-0047) was to develop erasable optical recording hardware and media subsystems for integration into Kodak's commercial large format drive and library system. In addition to delivering an Advanced Development Model (ADM), contract funding would also permit Eastman Kodak to accelerate its plans to develop and bring to market a magneto-optic (M-O) version of the commercially available 2000E Optical Disk Drive and Library System

Portrayed in Figure 1.4-1 is the proposed system that would be integrated with other storage devices (magnetic disk and magnetic tape) as part of a Hierarchical Storage Management (HSM) system.

Figure 1.4-1 Rome Laboratory System Configuration



The approach employed in the program was to design erasable subsystems, utilizing and/or leveraging the commercial write-once design, such that an offering of a commercial erasable drive in the future would require a minimum level of engineering work. Thus, the engineering task was to focus on areas under development that would expedite development of an erasable MO system. The subsystems discussed in this report are the key technologies that have significant linkages to the commercial product family. They are: (1) the optical head and analog electronics; (2) magneto-optical media with a servo written format; (3) head-to-media performance metrics; (4) the drive firmware.

1.2 Summary

Due to delays in bringing to market Kodak's System 2000E Optical Disk Drive, the HCOJ program was not able to leverage many of the essential technology subsystems needed to deploy an ADM. In light of Kodak's revised 2000E development schedule the proposed contract deliverables have been reduced in scope. The contract re-plan favored an approach that would identify, either by hardware design or subsystem demonstration, the technology components needed to deliver an ADM.

In addition, during the contract performance period, Kodak decided not to commercialize an erasable 14-inch product, due to business case considerations. However, the subsystems successfully developed under this contract dramatically minimized any foreseeable risks in achieving the final objective. These subsystems include:

Universal MO/Phase Change Optical Head Design

The ADM design strategy was to demonstrate multi-function operation from a single optical head that would have the ability to read and write on WORM or MO media. Using this design a prototype head was fabricated and used extensively on MODS. Although not a contract deliverable, the multifunction design provided a path forward for a commercial product.

Sampled Servo Tracking on MO Media

The tracking system employed by the System 2000E optical disk drive is the push-pull method. Although a proven method with WORM media, sampled servo tracking on MO media was only shown to work in theory. After the fabrication of the multifunctional head, this method was show to work as predicted.

Bias-Magnet Device

In MO recording the media must be subjected to an externally applied magnetic field to orient the material in the proper direction. In this application Eastman Kodak has developed a novel bias magnet device composed of a cylindrical multi-pole permanent magnet. Using the eddy-current fields generated within the rotating aluminum substrate the device required no external power supplies to position the magnet in it's correct orientation.

MO Media Fabrication

It was shown that the fabrication of rewritable MO disks could leverage and integrate much of the commercialized WORM media manufacturing facilities.

System Performance

The sensitivity of MO media to write power was of major concern since little was know about the performance of the head-to-media interface. This was a major area of concern since many of the subsystems being tested (i.e., optical head, media, detection and tracking electronics) had never been tested together as a system, let alone individually. Although many months were devoted to the investigation the results obtained clearly showed that there were no technical or physical impediments that would prevent integrating the MO subsystems into a 2000E optical disk drive.

The following sections document the major subsystems, their design methodology and the integration path forward to deploy an ADM. For complete technical details we refer the reader to the System/Sub-system Design Plan

2.0 ERASABLE SUBSYSTEMS

2.1 Multifunction Optical Head and Analog Electronics

A schematic of the multifunction optical head is shown in Figure 2.1-1. The head is leveraged from the current System 2000E WORM optical head and its properties are summarized in Table 2.1.1

The 30 mW SDL laser diode has undergone extensive testing and has been shown to be extremely reliable with very low relative intensity noise [i]. The laser is collimated with a 7.5 mm focal length, precision glass molded (Kodak A375) lens. The optical stack uses the same glass types as our commercial product to provide achromatic beam expansion [ii], [iii]. The coating on the partial PBS was redesigned to maximize the MO data signal and provide acceptable head efficiency as described in Table 2.1.1. A turning prism reflects the beam up to the 0.55 numerical aperture (NA) molded glass objective lens. A 1.1 mm coverplate and the 90 µm coversheet for both the MO and WORM media packages compensates for the lens design substrate thickness of 1.2 mm.

Figure 2.1-1 Multifunction 680 nm, 0.55 NA Optical Head

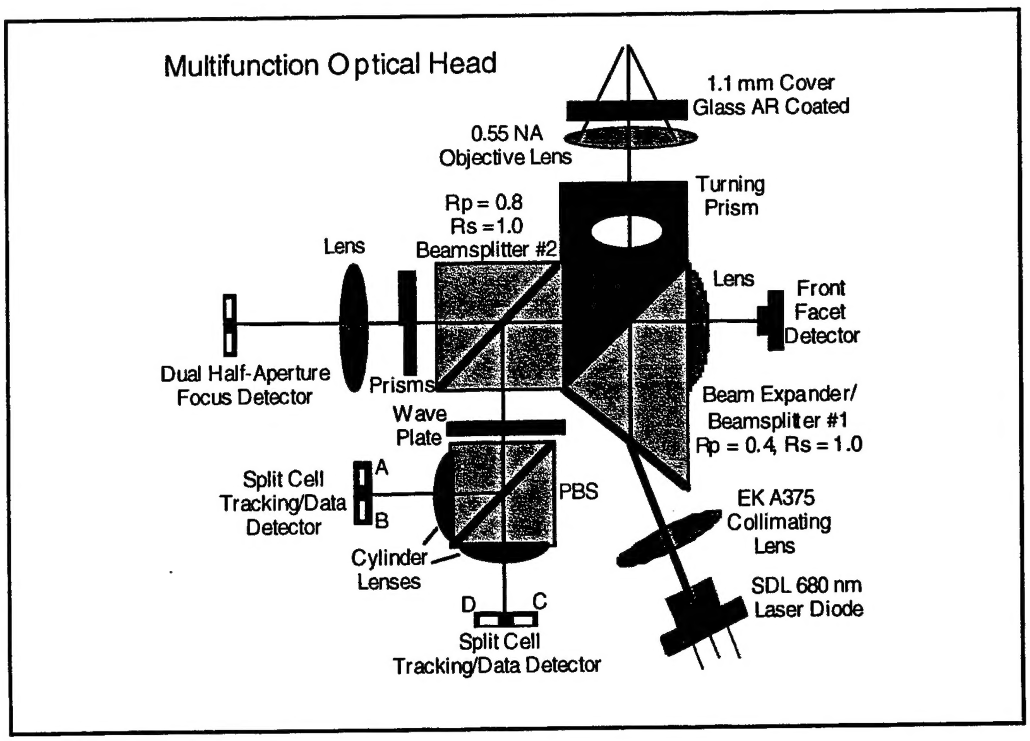


Table 2.1.1 Properties of 680 nm Multifunction Optical Head

Media Type	14" MO or WORM
Substrate	90 μm coversheet
Wavelength	680 nm
Spot Size FWHM	0.70 μm
Numerical Aperture	0.55
Head Efficiency	30%
Power at Disk (Maximum):	8 mW
Focus Method	Dual Half Aperture
Tracking Method	Full Aperture Push-Pull

The return path is designed to maximize the data and tracking detection signal-to-noise ratio. The return beam is reflected by the partial polarization beamsplitter #1. The dual half aperture focus detector receives 20% of the p-polarization component of the return beam. The reflected light from beamsplitter # 2 is directed though a waveplate that corrects for media and head phase shifts and results in approximately equal intensity from the two beams from the polarization beamsplitter (analyzer). The two beams are brought to line foci (elongated in the cross track direction) on a pair of bi-cell detectors that provide signals A, B, C, and D for tracking error and data detection. These signals are processed by the multifunction data/tracking electronics as shown in Figure 2.1-2. The push pull tracking signals are given by:

$$\text{WORM TES} = (A + C) - (B + D) \quad (1)$$

$$\text{MO TES} = (A + D) - (B + C) \quad (2)$$

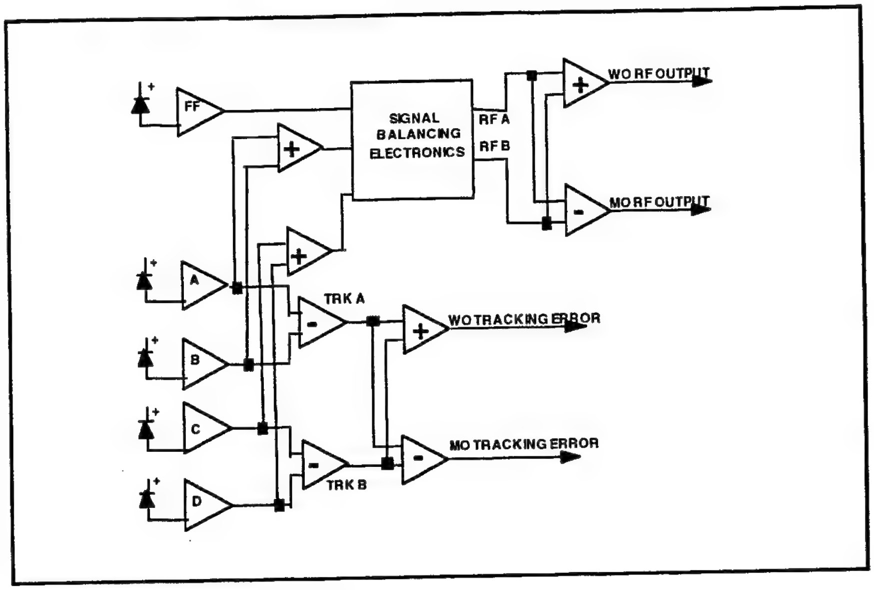
where the tracking error signal is sampled from the diffraction effects over servo written tracking pads (long data marks). The data signals are given by:

$$\text{WORM DATA} = (A + B) + (C + D) \quad (3)$$

$$\text{MO DATA} = (A + B) - (C + D) \quad (4)$$

The signal balancer electronics utilize variable gain amplifiers to minimize the effects of birefringence and laser power fluctuations on the data signals RF A and RF B before the final sum (WORM) and difference (MO) are generated according to equations 3 and 4. This additional step is required with a birefringent coversheet in a multifunction system.

Figure 2.1-2 Schematic of the Multifunction Data/Tracking Detection Electronics



2.1.1 Path Forward

Using the standard 2000E optical head manufacturing process, four multi-function heads were assembled and tested. Each optical stack, after passing final inspection was integrated to a head electronics board (HEB), and then the complete subsystem was bench tested to verify the assembly process. At this point in the 2000E manufacturing process the optical heads would be directly integrated into a drive for final testing.

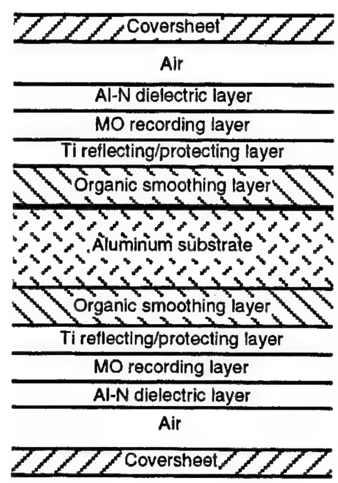
To further understand the interface characteristics between the ADM heads and a 2000E optical drive it was envisioned that MODS would be used to verify the operational performance of the ADM heads, however due to the contract re-plan this task was not achieved. Photo A shows the commercial 2000E optical head and headboard (short board on left) next to the custom ADM optical headboard (long board on right). Also is the custom head cable (lengthened 3 inches) that interfaces the ADM to the commercial 2000E optical disk drive. Photo B shows an ADM head installed in the upper head slot within a standard 2000E drive.

2.2 Magneto-Optical Media and Servo Written Format

2.2.1 Disk Structure

A new simple trilayer disk structure was used. The disk structure, Al Substrate/Ti reflecting layer/MO layer/AlN antireflection layer, eliminates the second dielectric in the conventional quadrilayer structure [iv], while essentially maintaining its performance. Also, it eases some of the tight manufacturing tolerance limits involved in the quadrilayer structure. Ti metal layer can be deposited more easily and at a significantly higher rate than its dielectric counterparts, e.g., AlN or Si_3N_4. Figure 2.2.1-1 contains a side view detail of the MO disk structure.

Figure 2.2.1-1 MO Disk Structure Side View



Magneto-optic media was fabricated using a modified Balzers LLS-801 sputter deposition system. The sputter deposition is carried out using three cathodes for depositing a Ti reflector layer, a TbFeCo-based MO layer, and the AlN dielectric layer. During deposition, the substrate is rotated around an axis perpendicular to the sputtering cathode using a turn table affixed to the indexing drum. In this way, all three layers are deposited in sequence with no vacuum break. Subsequently, a protective polycarbonate coversheet is attached and the disk is cartridged identically to the 2000E product.

2.2.2 MO Layer Characterization

Recording Layer. The recording layer composition, thickness, and deposition conditions were chosen to provide the optimal combination of signal quality, recording power, and environmental stability. The sputtering pressure and film composition were adjusted for a coercivity less than about 10 kOe to enable static room temperature disk erasure using a large area electromagnet. This is a much faster method of initialization compared to dynamic erasure using a focused optical stylus. The circumferential variation in recording layer properties was negligible due to the rotating substrate motion, and the radial variation in thickness was held within ±5% using a specially designed mask. Additions of small amounts of Zr and Pd [v] have been shown to enhance the intrinsic environmental stability and writing sensitivity of the MO layer.

Dielectric Layer. An AlN dielectric layer was used to optimize the Kerr rotation and reflectivity of the optical stack and, importantly, to provide corrosion protection for the MO layer. It was deposited by DC reactive sputtering of an Al target in an Ar and N_2 atmosphere. The reactive AlN sputtering process involves feedback control of the N_2 flow to maintain constant current at constant pressure. The AlN mechanical and optical properties, as well as thickness uniformity are critically important for the performance of the disk. Preparation of low stress and crack-free AlN layers is essential for providing long-term corrosion protection of the oxidation susceptible MO layer. AlN films with optimum properties were obtained by controlling the sputtering power, Ar:N_2 pressure ratio and total sputtering pressure. A radial thickness variation of less than ±5% was obtained. The measured refractive index at 680 nm for AlN is $n + ik = 2.06 + i0.01$. The low coefficient of absorption $k = 0.01$ is desirable for efficient optical performance.

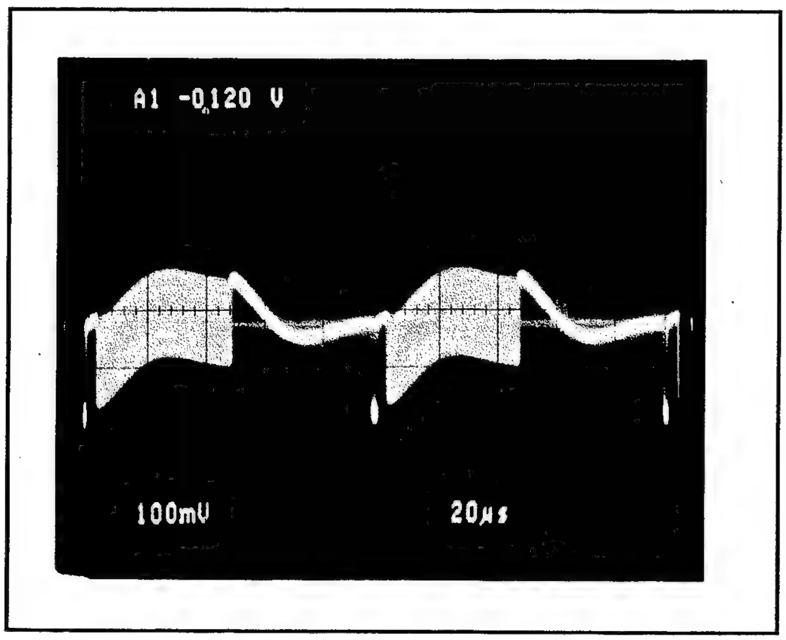
Reflector Layer. Ti metal was used as a reflecting layer. Ti metal has low thermal conductivity so in addition it acts as a thermal barrier between the MO layer and the surface smoothed aluminum substrate, thus improving the writing sensitivity of the disk. The Ti layer also provides corrosion protection for the MO media from the organic surface smoothing material. Its thickness uniformity was within ±5%, similar to the MO and dielectric layers. An additional beneficial effect of the Ti underlayer was to enhance the coercivity and squareness of the Kerr hysteresis loop, advantageous for low disk recording noise.

2.2.3 Cycle Life Test

To verify the media's ability to support numerous erasures a Life Cycles Test was performed on the MODS that cycled the MO media through 3,500 erase-write cycles. Although 10,000 cycles were proposed, a communication conflict between the MODS control software and the bias magnet's mechanical release actuator occurred. This conflict could not be resolved within the contract's period of performance and the test concluded after 3500 cycles. Even though 10,000 cycles were not achieved, phase margins above 30% were measured in all instances, which is above the System 2000E's shipping spec of 20%.

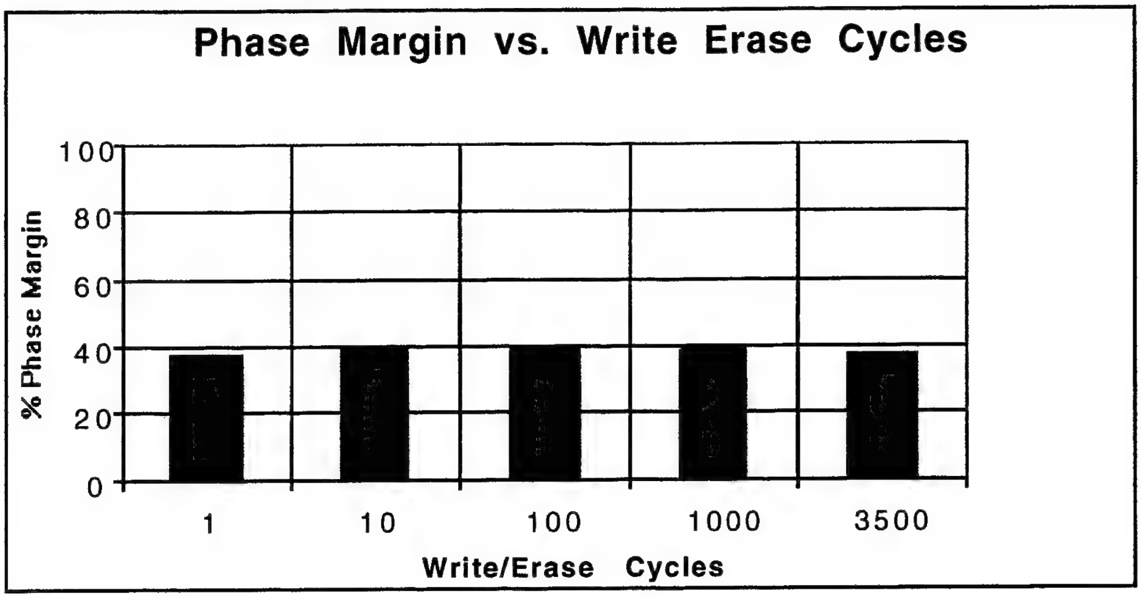
The test started by first writing a concentric track of 1 microsecond long tracking pads (media velocity of 12 meters/second) at a pad spacing of 100 microseconds. After the sample tracking servo was locked and tracking robustly, the system software cycled through a specified number of write and erase cycles. Figure 2.2.3-1 shows three servo written tracking pads between which the MFM data has been written. Data was only written in the first 50 microseconds of the sector to allow the RF amplifiers time to recover from the induced DC bias. Although the bias could be eliminated in hardware it was not needed to perform the cycle life test and had no impact on the results obtained.

Figure 2.2.3-1 Sample Tracking Pads and User Data



During each cycle the control software loaded the MFM data pattern switched the magnet's polarity, wrote data between the tracking pads and then erased that data. Phase margin data was recorded at 1, 10, 100, 1000 and at 3500 cycles. Figure 2.2.3-2 shows the results of this test.

Figure 2.2.3-2 Cycle Life Test



2.2.4 Media Formatting

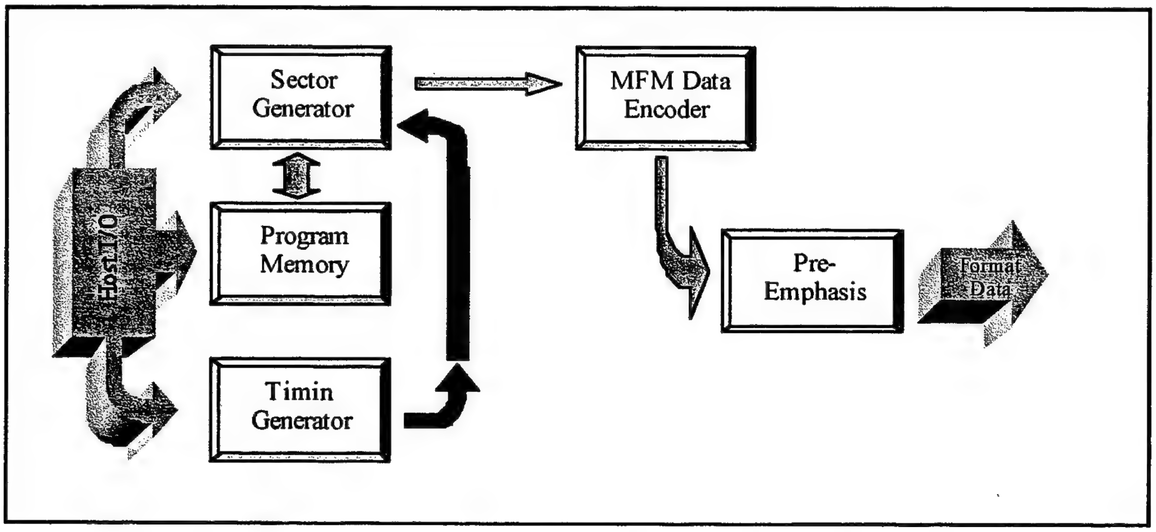
To format both MO and WORM media the MODS was equipped with a modified version of the formatting subsystems from the WORM production equipment (ProQuip brand). These modifications include custom developed hardware & software to create a robust formatting capability.

This approach has significant advantages in that it allows MODS to format and read back both media types using the multi-function capabilities of the MODS' optical head. In contrast using the production ProQuip WORM formatter would have required formatting MO media in an open-loop mode. This would require format verification to be performed using the MODS media tester.

Media formatting on MODS required transferring the ProQuip's formatting logic into a PLD that was designed and modified for MODS implementation. The hardware was modeled after a stored program processor commonly referred to as the "state machine" which controls the flow of data as the media is formatted.

The computer controlled software allows for the inputting and downloading the proper band parameters (depending on the band being formatted) to the formatter board, controlling the slide and spindle motors, controlling the write laser power, controlling the tracking servo, and calculating final position error at the end of each band. The open architecture of the state machine allows for the flexible programming of various sector formats. The hardware elements composing the state machine are shown in Figure 2.2.4-1.

Figure 2.2.4-1 Formatting State Machine



To test the MODS formatting capability, Band 4 of a WORM disk was formatted using a 10.2 GByte MFM media format. The disk was then tested in a 2000E production drive and was successfully used to start the drive, track on pads and read sector addresses. Although a MO disk was not formatted the same procedure would be identical.

2.2.4.1 Path Forward

Although it can meet the performance metrics for system integration TbFeCo Media has exhibited lower than expected resistance to high humidity conditions. The life tests designed to characterize the media's shelf life revealed media oxidation in all cases where high humidity existed. If further commercialization actions were taken, the MO Co/Pt Super Lattice[vi] media could confidently eliminate the corrosion artifacts found in the TbFeCo media.

Manufacturing uniformity was also a challenge in getting uniform media properties across the active region of the disk. It is believed that the uniformity problems would have been overcome by manufacturing several disks in succession with the expectation that a reasonable yield loss would produce a higher number of production quality MO disks.

2.2.5 Head-to-Media Performance Metrics

The main thrust of the dynamic testing is to ensure that the MO performance is similar to the production WORM system and that the MO system exceeds the contract requirements for data integrity, capacity (> 10 Gigabyte/Disk), and data rate (>1 Megabytes/sec). To verify these specifications, the MODS test platform was used to characterized the performance of the head-to-media interface. Photo C shows the control electronics and test instrumentation of MODS. Photo D shows the spindle, MODS multifunction optical head and MO disk. Photo E shows the MODS Graphical User Interface.

The sensitivity of MO media to write power is of major concern since it affects laser power calibration in the drive. Since inflection detection is used in the drive, small write power errors can cause significant mark length errors.

In operation Optimum Recording Power (ORP) is expected to behave linearly as a function of media velocity. It varies from its lowest value at the inner radius of a band to its maximum value at the outer diameter. Although ORP is calibrated at a fixed velocity scaling the laser power for appropriate media velocities has been the method of choice for this detection system. The objective of these experiments are to determine the range of write power at which a phase margin of greater than 20% can be maintained and to determine conditions which produce the largest write power tolerance.

All performance measurements were achieved using a pulsed write strategy. Since the MO media's response to laser power was notably different than WORM media, the implementation of a write strategy was needed.

By design the 2000E drive architecture uses an NT write strategy Figure 2.2.5-1. Experiments have shown that using this write strategy on MO media produces less than optimal phase margin (less than 20%). The simplest approach to using a write strategy was to break the write clock pulses into a series of 50 ns pulses that have a 50% duty cycle. Therefore each 50 write pulse would be converted into a pulse that was high for 25 ns then low for the remainder of the cycle. Figure 2.2.5-1 shows the write strategy version of the NT pattern.

Figure 2.2.5-1 NT Write Strategy

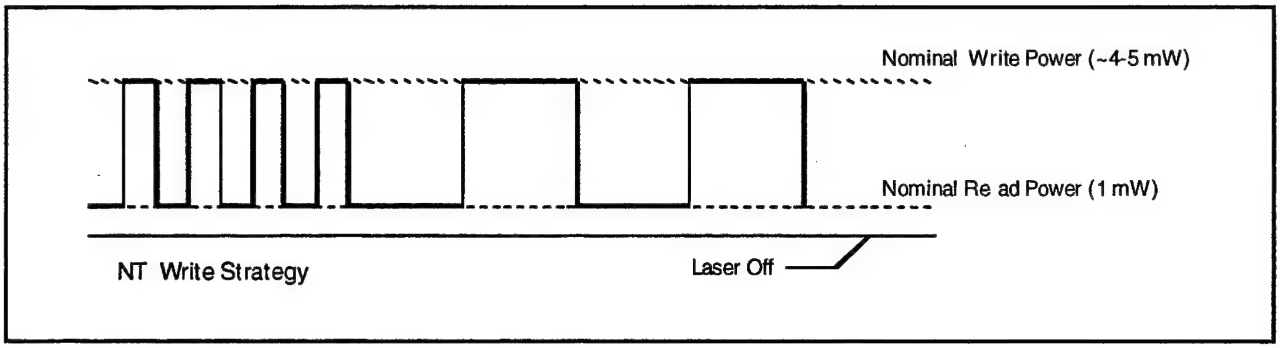
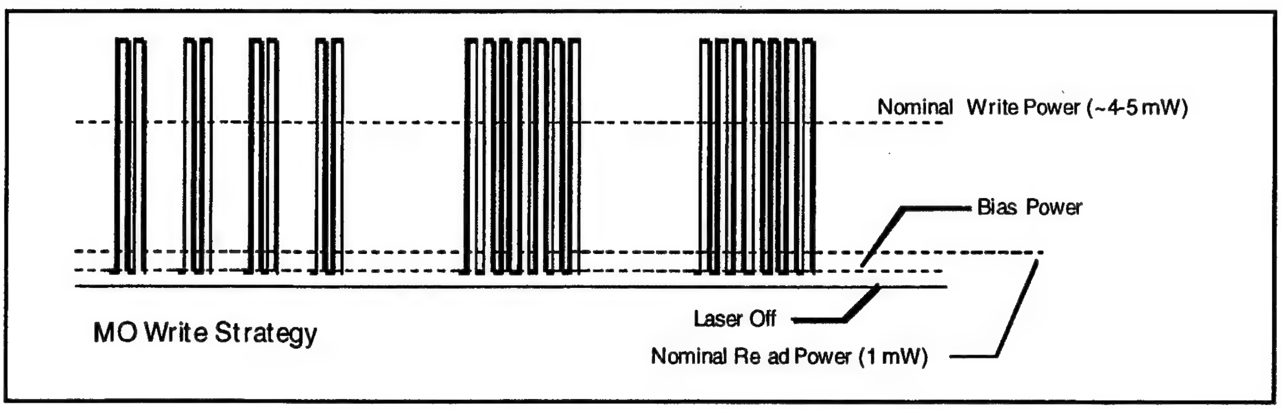


Figure 2.2.5-2 Pulsed Write Strategy



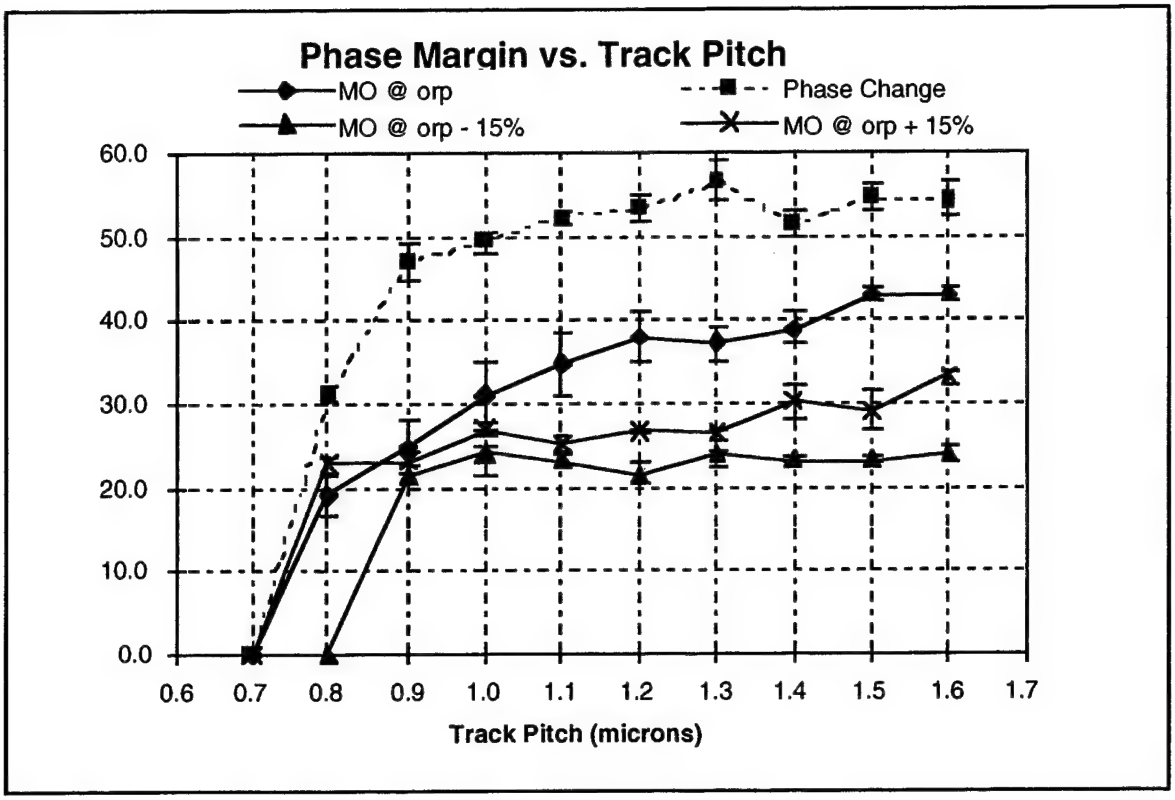
Since the system's phase margin could be almost doubled by using this pulsed write strategy, all experiments were performed using this implementation.

2.2.6 Minimum Track Pitch

To determine system performance as a function of track pitch, phase margin was measured on the center track in a group of five, where adjacent tracks were written at a constant track pitch. Track spacing was reduced, from 1.6 microns in 0.1 micron increments, until 0% phase margin was achieved. Since variations in write powers have the most dramatic effects on system performance the test was repeated with write power 15% above and 15% below ORP. All tracks were written using a pulsed write strategy with the results plotted in Figure 2.2.6-1.

Using the universal capability of the MODS head, phase change media was also measured at ORP for comparison.

Figure 2.2.6-1



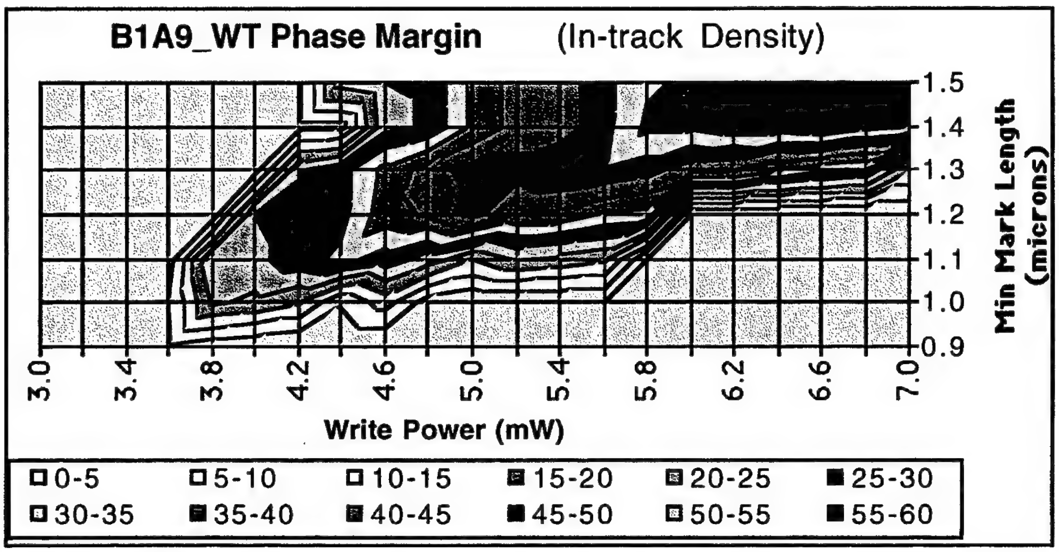
Inspection of Figure 2.2.6-1 shows that adequate performance, above 20% phase margin (shipping spec for the 2000E drive), can be achieved in all cases for track spacing greater that 0.9 microns.

Realizing that other system losses, such as focus or tracking offsets could further reduce phase margin, a minimum track pitch of 1.5 microns is recommended for the media format. This track spacing provides enough separation such that phase margin losses due to other system tolerances including erasure will be kept to a minimum.

2.2.7 Minimum Mark Length

Experiments were performed to determine the minimum mark length for each write strategy using a read and bias power of 1.5 mW. During this experiment the linear velocity was varied to produce mark lengths ranging from 0.7 microns to 1.6 microns at a constant data rate of 10 Mbit/s.

Figure 2.2.7-1



2.2.7.1 Path Forward

All experiments performed to indicate that the MO head-to-media interface performance metrics are well above the minimum specifications needed to integrate the MO media, optics and electronics into a 2000E optical drive.

2.2.8 Drive Firmware

The Drive Subsystem firmware is a collection of many sub-state machines that sequence through a series of operations such as DriveStart, DriveRead, DriveWrite, etc. to execute a host command. As a collective these state machines are executed when needed and are responsible for drive operation. Since erase is much like write, except that erase requires a DC laser level and reverse magnet polarity, erase is described as a write process.

2.2.8.1 Path Forward

Much of the Drive Erase firmware is architecturally in place in the current 2000E drive firmware but has not been tested. The implementation of the erase functionality would still require software coding to take place to take advantage of these features.

3.0 CONCLUSIONS

A key component of the "platform approach" of the 2000E was to provide the capability to implement future enhancements with reduced resources and cycle times. The Rome Laboratory erasable optical project has attempted to utilized the platform effectively to achieve delivery of an ADM. The direct compatibility of the multifunction optical head, media substrate and cartridge, and implementation of featureless servo written formatted media would provide the capability to commercialize a multifunction drive in the future.

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i E. C. Gage, S. Beckens, P. Cronkite, S. Dohmeier, D. Kay, M. Meichle, and R. Metzger, "Low Noise, High Reliability 680 nm Optical Head Enables Robust 14.9 Gigabyte/Disk Product," SPIE Proc. Vol. 2514, Optical Data Storage '95, eds. G. R. Knight, H. Ooki, and Y. S. Tyan, p. 129 (1995).

ii D. B. Kay, S. B. Chase, E. C. Gage, and B. D. Silverstein, "Write Noise from Optical Heads with Non-Achromatic Beam Expansion Prisms," SPIE Proc. Vol. 1499, Optical Data Storage '91, eds. J. J. Burke, T. A. Shull, and N. Imamura, p. 281 (1991).

iii E. C. Gage and B. J. Bartholomeusz, "Directional Asymmetries due to Write-Laser Mode Hopping during Optical Recording," J. Appl. Phys. 69, 569 (1991).

iv T.W. McDaniel and F.O. Sequeda, Appl. Phys. Commun. 11, 427 (1992).

v T.K. Hatwar, J. Appl. Phys. 70, 6335 (1991).

vi T. K. Hatwar, Y. S. Tyan, and C. F. Brucker, "High-performance Co/Pt multilayer magneto-optical disk using ultrathin seed layers" J. Appl. Phys. 81, pp. 3839-3841(1997)

vii CLIN 2 – CDRL item 3: System/Sub-system Design Plan; Delivered March 12, 1997

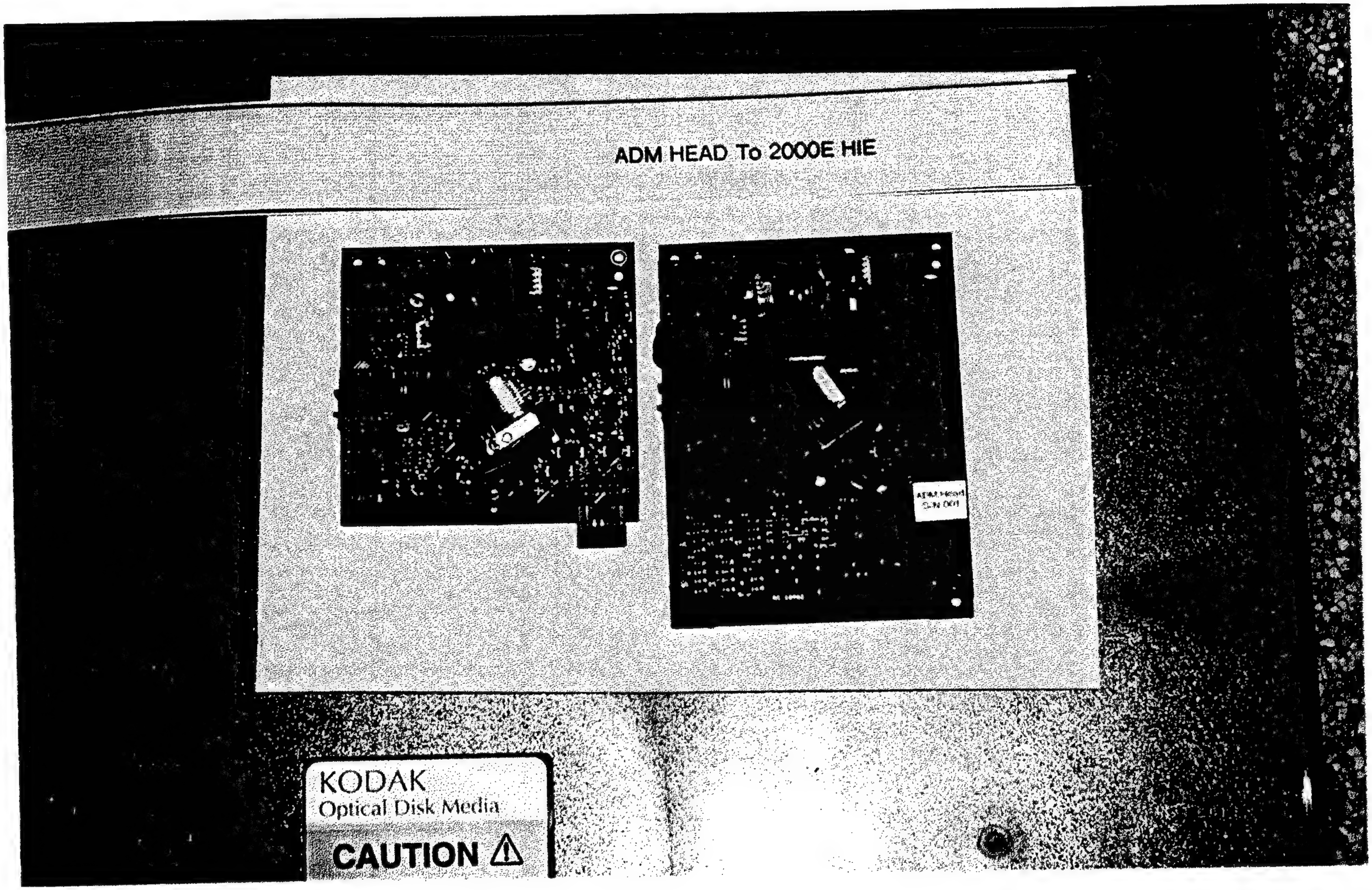

Photo A: 2000E Head, ADM Head, Custom ADM Head Cable

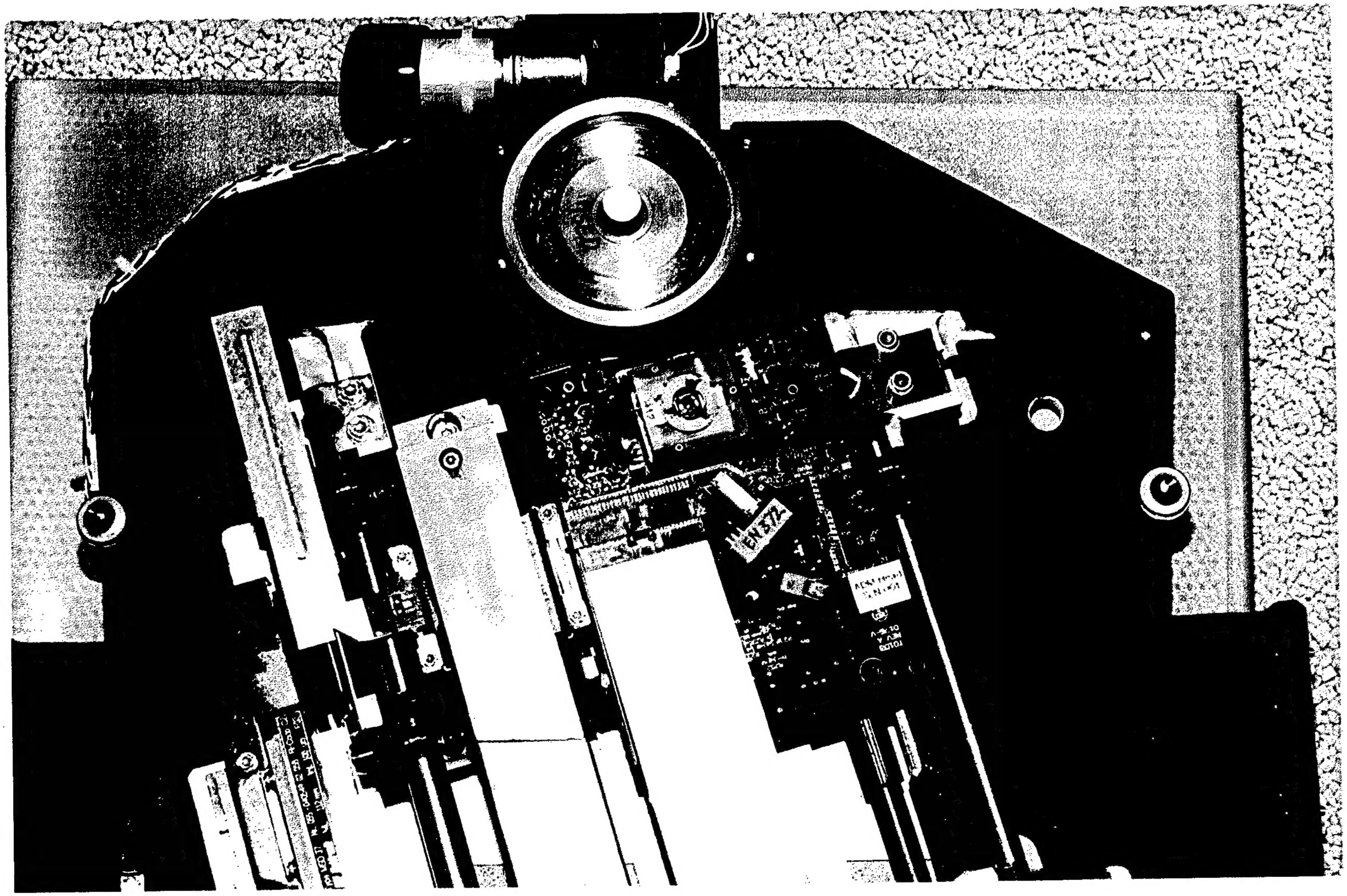

Photo B: ADM Head Insalled in the Upper Head Slot of a 2000E Drive

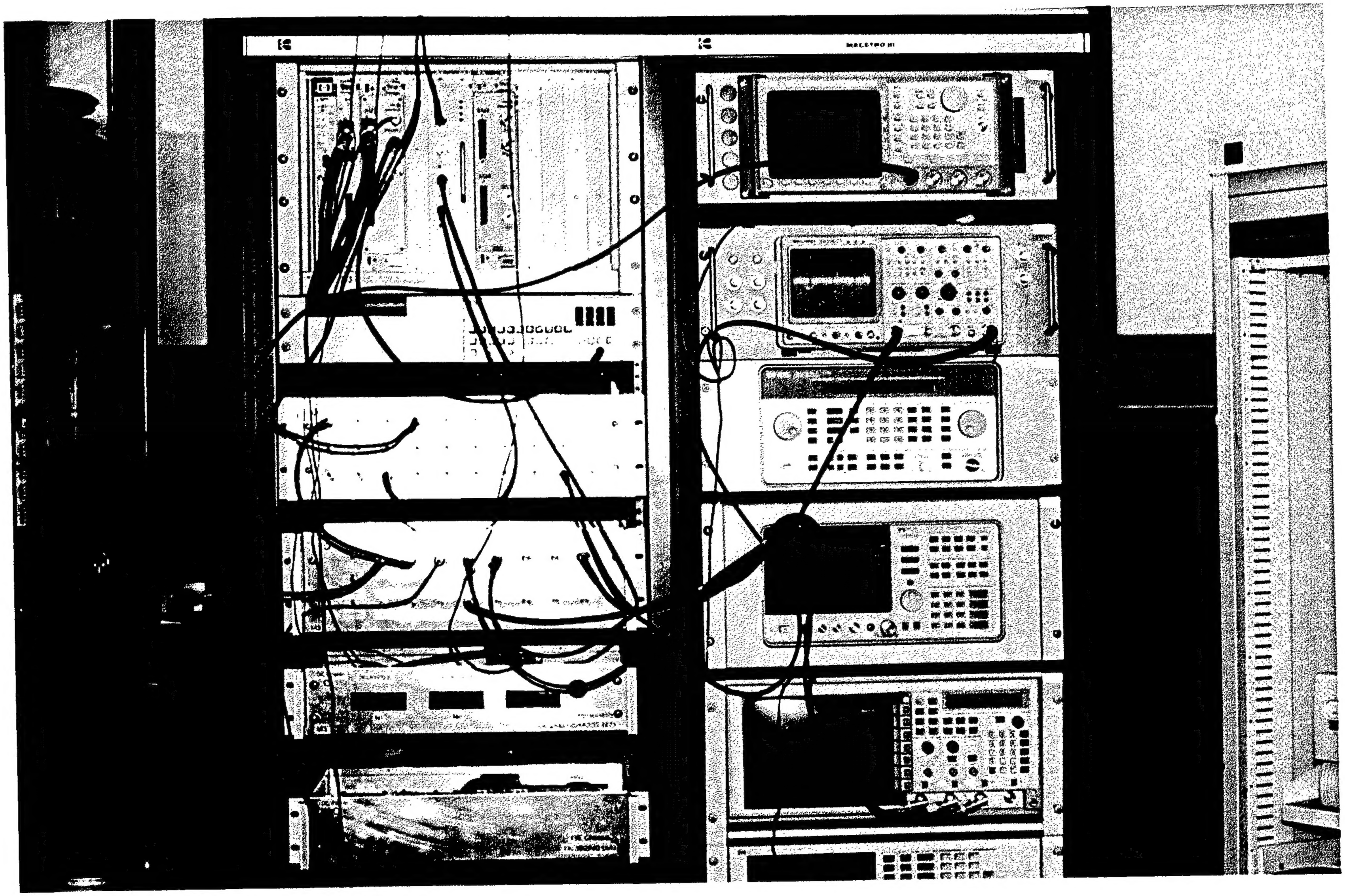

Photo C: MODS Control Electronics and Test Instrumentation

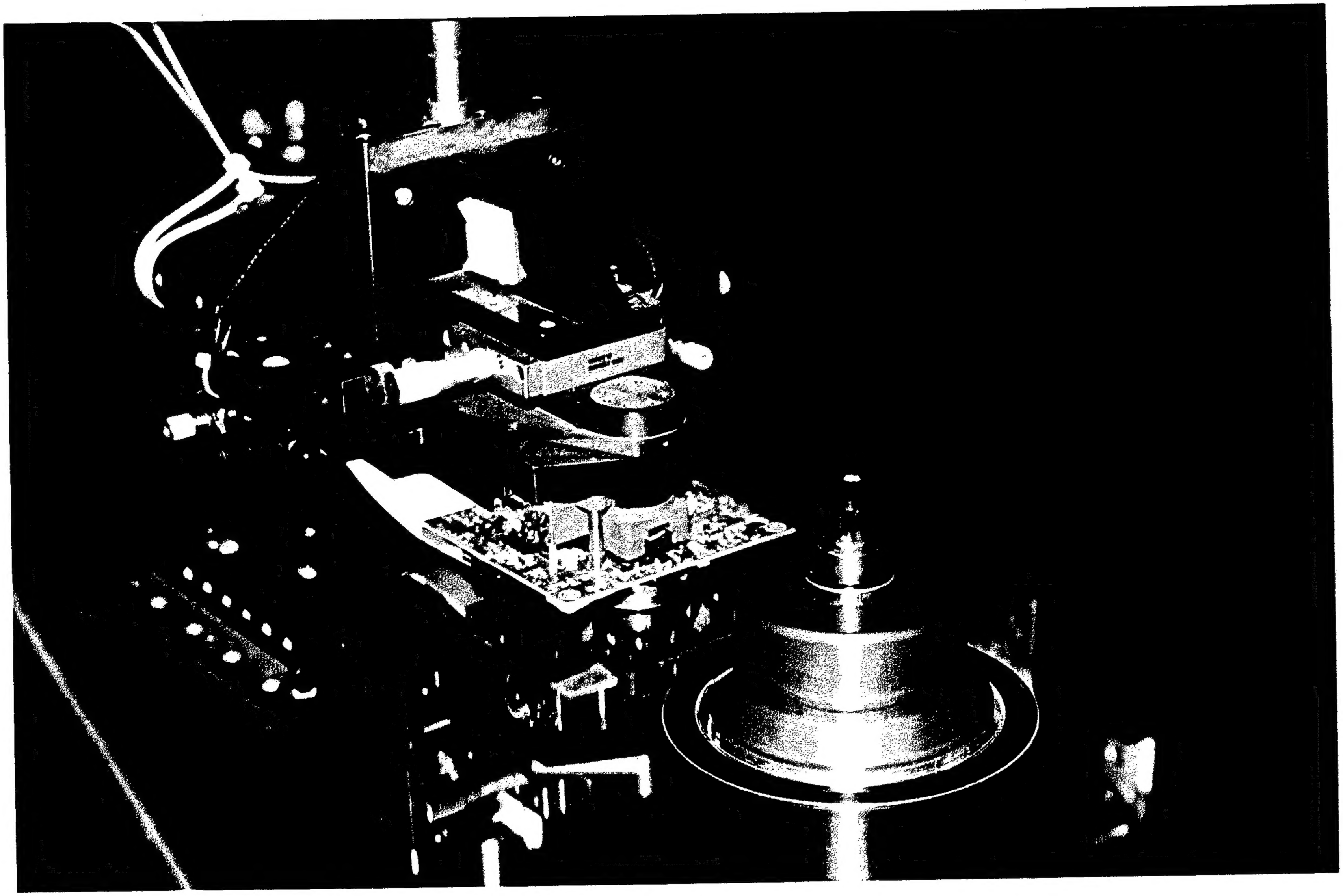

Photo D: Spindle, MO Disk, and MODS Multifunction Optical Head

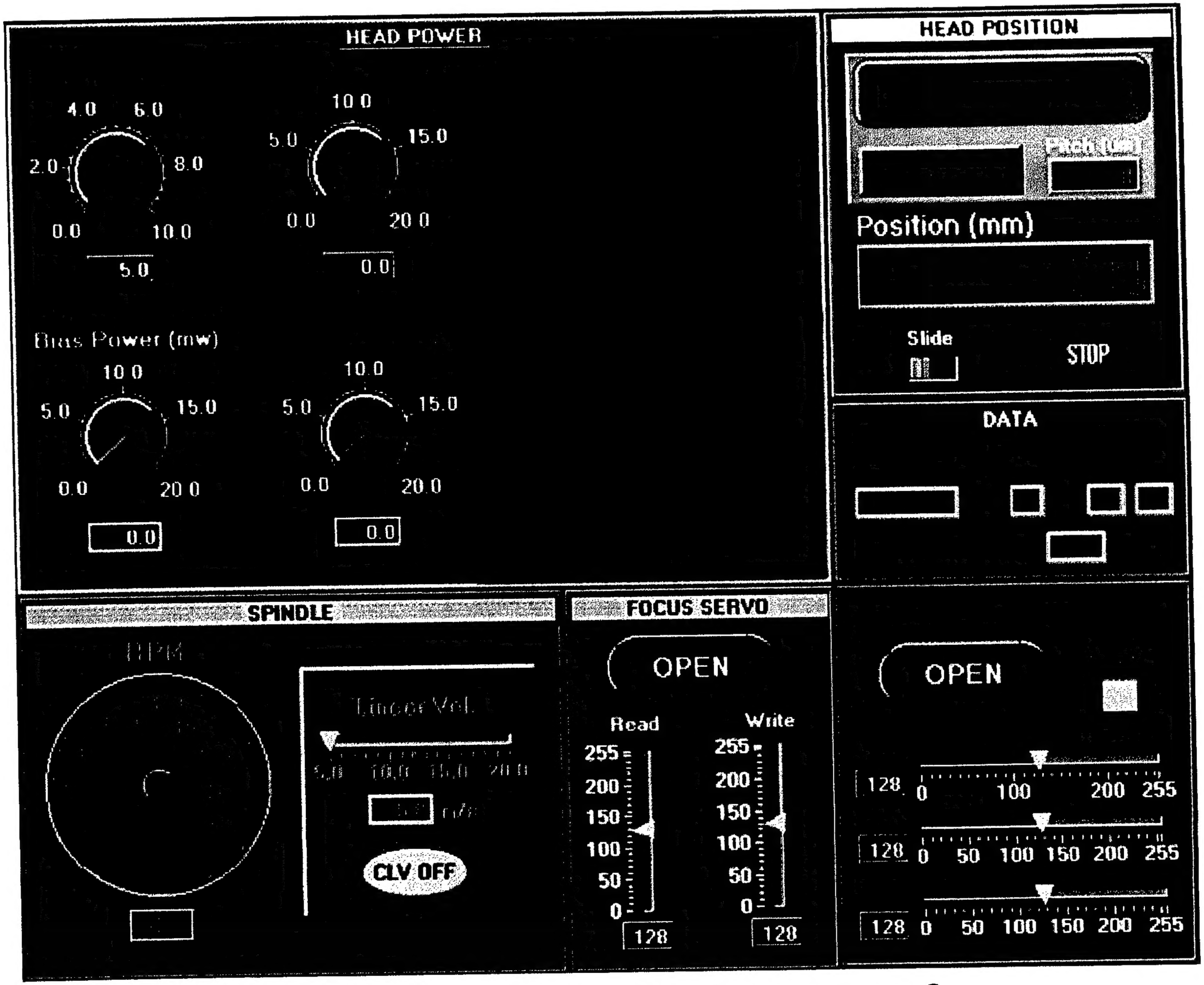

Photo E: MODS Graphical User Interface